Simulation of Ionospheric Response to Solar Disturbance Mechanisms

Abstract

We propose a three year study to investigate the ionospheric response to solar disturbances. One of the most important solar initiation mechanisms for geomagnetic storms are coronal mass ejections (CMEs) [*Gosling et al.*, 1991]. Accordingly, the first step of our study is to investigate geoeffective parameters associated with interplanetary coronal mass ejections and the magnitude of their impact on the earth's ionosphere. For this task, we will use a three-dimensional, axisymmetric self-consistent MHD code to study the initiation and propagation of CMEs from the Sun to the Earth and to predict parameters such as the duration and strength of the southward turning of the interplanetary magnetic field, the shock arrival time and its strength, and the strength and duration of the solar wind ram pressure. We will then use the field line interhemispheric plasma (FLIP) model to predict the ionospheric response to the CME, using the MHD code predictions of geophysical parameters. The predicted ionospheric response will be compared to observations from ground-based measurements by ionosondes, radars, and satellite measurements of total electron content. The ionospheric investigation will include the magnitude of positive/negative ionospheric storms, the links between storm phases and changes in the thermospheric composition (atomic to molecular composition), and the nature of these composition differences.

Our goal is to investigate the feasibility of providing a self-consistent coupling between solar propagation models, which typically stop at 1 AU, and ionospheric models which assume an input function as a proxy to solar activity. Successful completion of this goal will mark the first time such a self-consistent coupling has been done.

Specifically, this proposal addresses the following questions.

1. How well can we model geoeffective physical parameters such as a) the duration and strength of southward turning of the IMF at 1 AU, b) the shock arrival time and its strength, and c) the strength and duration of the ram pressure?
2. How effectively can we correlate geomagnetic storms and conventional magnetic indices with the modeled CME physical parameters?
3. How well can we model ionospheric storms based solely on the modeled CME physical parameters?

In short, this proposed program is aiming to lay the foundation for the development of a science-based prediction technology for space weather.

Simulation of Ionospheric Response to Solar Disturbance Mechanisms

1. Technical Description

1.1 Objectives and approach

The objective of the work proposed here is to examine fundamental diagnostics of interplanetary coronal mass ejections (CMEs), to use these parameters to categorize the interaction of CMEs with the near-earth space environment, and to investigate the ionospheric response to these solar disturbances. This objective will be met by coupling two existing models--a three-dimensional, axisymmetric self-consistent MHD code to study the initiation and transport of CMEs [*Wu et al.,* 1999], and an interhemispheric ionospheric plasma model [*Richards et al.,* 1998*; Torr et al.,* 1990] to predict the ionospheric and neutral thermospheric response to CMEs.

Successful completion of this goal will enable investigation of the ionospheric response to individual CME events. This integrated approach thus tracks CMEs from their initiation at the sun, to their first interaction with the Earth's magnetosphere, and finally to their ultimate perturbation on the earth's ionosphere. The proposed objective is consistent with the Air Force Office of Scientific Research (AFOSR) space science objectives that include "...coronal mass ejections (CMEs) and solar flares; [and] the coupling between the solar wind, the magnetosphere, and the ionosphere". It directly contributes to the AFOSR goal "...to develop a global, coupled solar-terrestrial model that connects solar activity with the deposition of energy in the Earth's upper atmosphere".

Magnetic storms and their consequences are the biggest dynamical features of space weather in the Earth's magnetosphere. The cause of the largest magnetic storms are fast interplanetary coronal mass ejections and their upstream interplanetary sheaths. The physical cause of magnetic storms is solar wind energy transfer due to magnetic reconnection between the interplanetary southward magnetic fields and the northward Earth magnetopause magnetic fields. Thus it is necessary to have large amplitude and long duration IMF B_S events to have storms with $D_{ST} < -100$ nT.

Knowledge of the formation and propagation of a CME is only the first of several questions that need to be investigated. Of great practical interest is the degree of interaction between the CME and the Earth. *Tsurutani et al.* [1988], from a statistical analyses, have shown that only one out of six fast CMEs create strong magnetic storms because the IMF B_S conditions were not met in 5 out of 6 cases. Thus the goal of predictions should be to not only predict the direction of a CME, but also the speed of the CME and its field intensity, direction and duration. Simply to detect/predict that a CME will hit the earth's magnetosphere is clearly insufficient for storm warning purposes.

The ultimate topic of interest is the question of how the earth's ionosphere will be affected by the CME, not just at auroral latitudes but in a more global manner. Geomagnetic storms lead to profound disturbances in the ionosphere and neutral upper atmosphere. Storm-time energy deposition leads to atmospheric disturbances characterized by increases in temperature, by changes in neutral composition, and by changes in the height and density of the ionosphere. These disturbances propagate from auroral latitudes to lower latitudes with a response period of hours. The consequences of these changes are anomalous variations in the decay rate of artificial satellites and to disruptions in communications.

The scientific objective of this proposal is to understand the initiation and propagation of CMEs from the Sun to near-Earth space and then to determine the ionospheric perturbation caused by the CME. Specifically, this proposal addresses the following problems.

1. How well can we model geoeffective physical parameters such as a) the duration and strength of southward turning of the IMF at 1 AU, b) the shock arrival time and its strength, and c) the strength and duration of the ram pressure?
2. How effectively can we correlate geomagnetic storms and conventional magnetic indices with the modeled CME physical parameters?
3. How well can we model ionospheric storms based solely on the modeled CME physical parameters?

The first problem is to analyze the performance of our solar MHD model and continue its development using data from previously analyzed CME events. Of special note is the emphasis not only on CME propagation, per se, but also on internal characteristics such as IMF and ram pressure. These parameters are essential in determining the likelihood of a CME resulting in a magnetic storm, which is the second problem to be addressed.

Atmospheric models typically include storm inputs via parameterization of conventional activity indices such as Kp and AE, and FLIP is no exception. To successfully couple the MHD calculation with the FLIP model, we must investigate the correlation between activity indices and CME physical parameters (the second part of the problem 2 above). This will have direct bearing on the final problem to be addressed--how well the modeled ionosphere matches actual values.

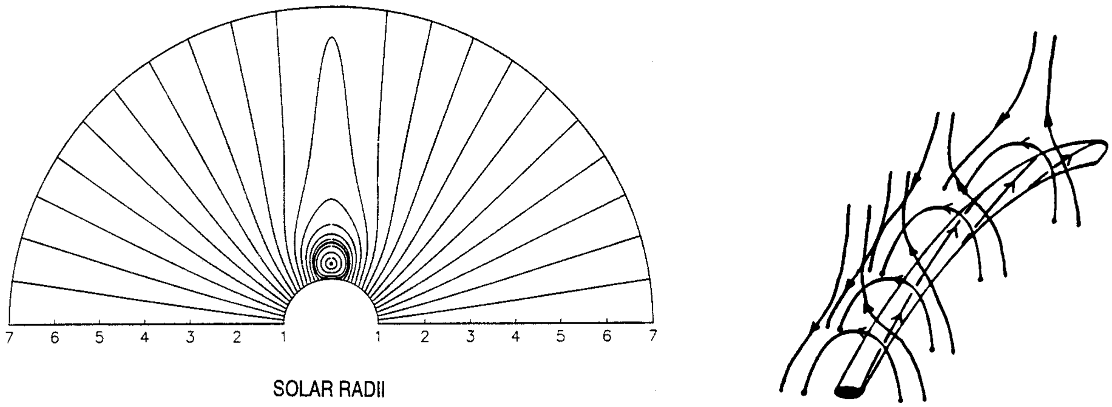
1.2 Available tools

In this section, we give detailed descriptions of the two models to be used in this study.

1.2.1 UAH Streamer-Flux-Rope Three-Dimensional Axisymmetric MHD Model

The University of Alabama in Huntsville streamer-flux rope three-dimensional axisymmetric self-consistent MHD model [*Wu and Guo*, 1997] is an extension of a previous streamer-bubble model given by *Wu et al.* [1995]. This model has been successfully applied to interpret a number of observed events from SOHO/LASCO to understand the initiation and propagation of CMEs [*Wu et al.*, 1997b,c].

In order to investigate Sun-Earth causality, we have extended the model to 220 R_s (solar radii) and beyond. This requires more than a simple extension of the computation domain. We must determine an undisturbed solar wind solution from 1 R_s to 220 R_s that is in agreement with the typically observed solar wind parameters at 1 A.U. To arrive at this solution, the polytropic index α is allowed to be a slow function of radial distance for the energy equation which varies from 1.03 to 1.46 from 1Rs to 1.A.U. This gives solar wind parameters which closely resembles the empirical values of solar wind at 1 A.U. and 1 R_s. A detailed account of this work is given by *Wu and Guo* [1997] and *Wu et al.* [1999]. The computed magnetic field configuration viewed in the solar meridional plane is shown in Figure 1a, and a schematic representation of the 3-D view of this magnetic field configuration is shown in Figure 1b. With the streamer and flux-rope solution as the pre-event state shown in Figure 1, we introduce an additional current in the flux-rope to mimic observations which causes the flux-rope to erupt and the streamer and flux-rope system to destabilize. Subsequently a CME is launched. This model has successfully modeled the 1997 Jan 6-12 Sun-Earth connection event. In addition, the model outputs agree well with measured coronal parameters by SOHO/LASP and solar wind parameters measured by WIND spacecraft at Earth's environment (1 AU). Details are published in *Wu et al.* [1999].



(a) **(b)**

Figure 1. The initial state for the simulation. (a) The computed magnetic field configuration of the streamer and flux-rope system projected on the sun's meridional plane, and (b) The schematic description of a three-dimensional view of the streamer arcade system with a filament in it.

The numerical scheme and boundary conditions used for this model are:

(i) The two-dimensional explicit combined scheme [*Wu et al.*, 1995] has been extended to a three-dimensional axisymmetric (i.e. 2.5 dimensions) MHD model. The essence of this combined scheme is to use different numerical methods to treat different governing equations, according to their physical characteristics. In the three-dimensional axisymmetric ideal MHD equations, the continuity and energy equations are discretized by the second type upwind scheme, the momentum and magnetic induction equation by the Lax-Wendroff scheme. A staggered grid is used to achieve high accuracy and to avoid sawtooth oscillations. This scheme was found to be stable and reliable. The initial streamer obtained by using this scheme [*Wu et al,*. 1995; Wu *et al.*, 1997a,b,c] is almost identical with previous results [*Steinolfson et al.*, 1982; *Wang et al.*, 1993].

(ii) In order to study the cavity flux-rope in the closed region of the streamer, we will use a much finer grid to increase the numerical resolution. In the study of photospheric shearing (another observed mechanism for CME initiation), which requires a relatively long time scale, explicit methods may be inappropriate due to their inherent limit of time steps. In our 2.5-D code, we have incorporated a semi-implicit operator in the momentum equation as an option. The semi-implicit method for solving time-dependent MHD equations was first introduced in the simulation of laboratory plasmas [*Harned and Kerner*, 1985; *Harned and Schnack,* 1986]. Then, it was successfully used in simulating coronal plasmas [*Mikic et al*, 1988; *Mikic and Linker*, 1994]. The introduced semi-implicit term in the momentum equation modifies the dispersion relations of the short wavelength modes while accurately treating the long wavelength modes, thus enabling the time-step to exceed the CFL (Courant-Friedrichs-Lewy) limit for Alfvén and magneto-acoustic waves. The semi-implicit operator we use is similar to *Mikic et al.* [1988]. The resulting large, sparse matrices are inverted used the bi-conjugate gradient method [*Jacobs*, 1981].

(iii) Boundary conditions are crucial in transient MHD computations [*Wu et al.*, 1996]. In the case of flow crossed boundaries, the boundary conditions must be specified according to the characteristic theory [*Hu and Wu*, 1984; *Wu and Wang*, 1987; *Sun et al.*, 1995] to assure self-consistency of the numerical solutions [*Wu et al*., 1996]. We have used characteristic boundary conditions at the inner boundary because the flow is subsonic and Sub-Aflvénic and non-reflecting boundary condition [*Wu and Wang*, 1987; *Sun et al*., 1995] at the outer boundary for supersonic and super Alfvénic flows.

1.2.2 Field Line Interhemispheric Plasma (FLIP) Model

The field line interhemispheric plasma (FLIP) model has been used in numerous ionospheric studies over the past 20 years [e.g. *Richards and Cole*, 1979; *Richards*, 1986; *Torr et al.*, 1990; *Richards*, 1990; *Richards et al.*, 1998]. The main component of the FLIP model calculates the plasma densities and termperatures along entire magnetic flux tubes from 80 km in the northern hemisphere through the plasmasphere to 80 km in the southern hemisphere. The equations solved are the continuity and momentum equations for O^+, H^+, He^+, and N^+ as formulated for the topside ionosphere by *St.-Maurice and Schunk* [1976]. The electron and ion temperatures are obtained by solving the energy equations [*Schunk and Nagy*, 1978]. Electron heating due to photoelectrons is provided by a solution of the two-stream photoelectron flux equations using the method of *Nagy and Banks* [1970].

In addition to the interhemispheric solutions listed above, the FLIP model uses local chemical equilibrium to determine the densities of the ions: $O^+(^2D)$, $O^+(^2P)$, NO^+, O_2^+, N_2^+,and solves diffusion equations for NO, $N(^2D)$, and $N(^4S)$ densities. The basic chemical scheme is described by *Torr et al.* [1990].

In order to simulate the ionosphere, the FLIP model requires three key inputs: the neutral atmosphere, the solar EUV flux, and the meridional component of the neutral wind. Neutral densities and temperatures are provided by the mass spectrometer and incoherent scatter (MSIS-86) model [*Hedin*, 1987] while the basic solar EUV flux is provided by our recently developed solar EUV flux model called EUVAC [*Richards et al.*, 1994].

In the last several years we have developed a number of algorithms to incorporate actual measurements (hmF_2, NmF_2, and T_e) into physical models [*Richards*, 1991; *Richards et al.*, 1995]. Most recently, we have developed an algorithm for determining what changes in the thermospheric atomic to molecular density ratio are needed to bring the model into agreement with measurements at the F2 peak height [*Richards et al.*, 1998; *Richards and Wilkinson*, 1998]. The purpose of all of these algorithms is to constrain as many parameters as possible in order to isolate inadequacies in specific model inputs. By adopting a subset of measurements as constraints, we have greatly enhanced the capability of the model to provide insight into the physical and chemical processes of the upper atmosphere.

The standard MSIS neutral atmosphere model [*Hedin*, 1987] is known to perform extremely well in an average sense, reproducing average satellite drag and mass spectrometer data to within about 15% [*Hedin*, 1988]. However, on particular days there may be large differences between measurement and model [see *Hedin*, 1988 Figure 4] and MSIS does not normally produce the large decreases in the atomic to molecular neutral density ratio that have been observed during ionospheric storms.

Richards et al. [1998] have developed a new, easy to implement, algorithm that enables the determination of the changes to the MSIS neutral atmosphere needed to explain differences between the measured and modeled N_mF_2. As the model steps in time, the neutral atmosphere is continually adjusted to bring the model into better agreement with the measured N_mF_2 similar to the way the winds are adjusted to reproduce the measured h_mF_2.

The density modification algorithm was first applied using data from Beveridge (38S,147E), Australia March 1-6, 1995 [*Richards et al.*, 1998]. Figure 2 shows the calculated (lines) and observed (circles) densities and temperatures. The curves with broken lines were obtained using the standard MSIS model while the solid curves were obtained when MSIS was modified. The lines with dots represent the monthly median values. Figure 2d shows that the modified Tn produced by the algorithm agrees well with the measurements by a Fabry-Perot interferometer (FPI). On most nights, the modified Tn agreed best with the FPI observations. In particular, both the measured and modified Tn usually increase after midnight and both increase very sharply after midnight on March 4, apparently in response to increased magnetic activity (*Kp*) towards midnight [Figure 2a]. The daytime N_mF_2 was close to the monthly median values (solid lines with dots) on March 4 and 6, but was severely depleted during the daytime on March 2 and 3. The ionosphere recovered on March 4 but was again depleted on March 5. Unlike March 2 and 3, which are close to the monthly median, the nighttime N_mF_2 was also severely depleted on March 5 and h_mF_2 was greatly elevated. The changes to the MSIS neutral density ratio are shown in Figure 2e. Note how well the model (solid line, no dots) reproduces the measured h_mF_2 while the neutral atmosphere is simultaneously being modified. The algorithms are also very stable. Our density modification algorithm could have been implemented by developing our own hydrostatic equilibrium model and using the MSIS model just to provide the lower boundary parameters, but this would have been a lot of unnecessary effort.

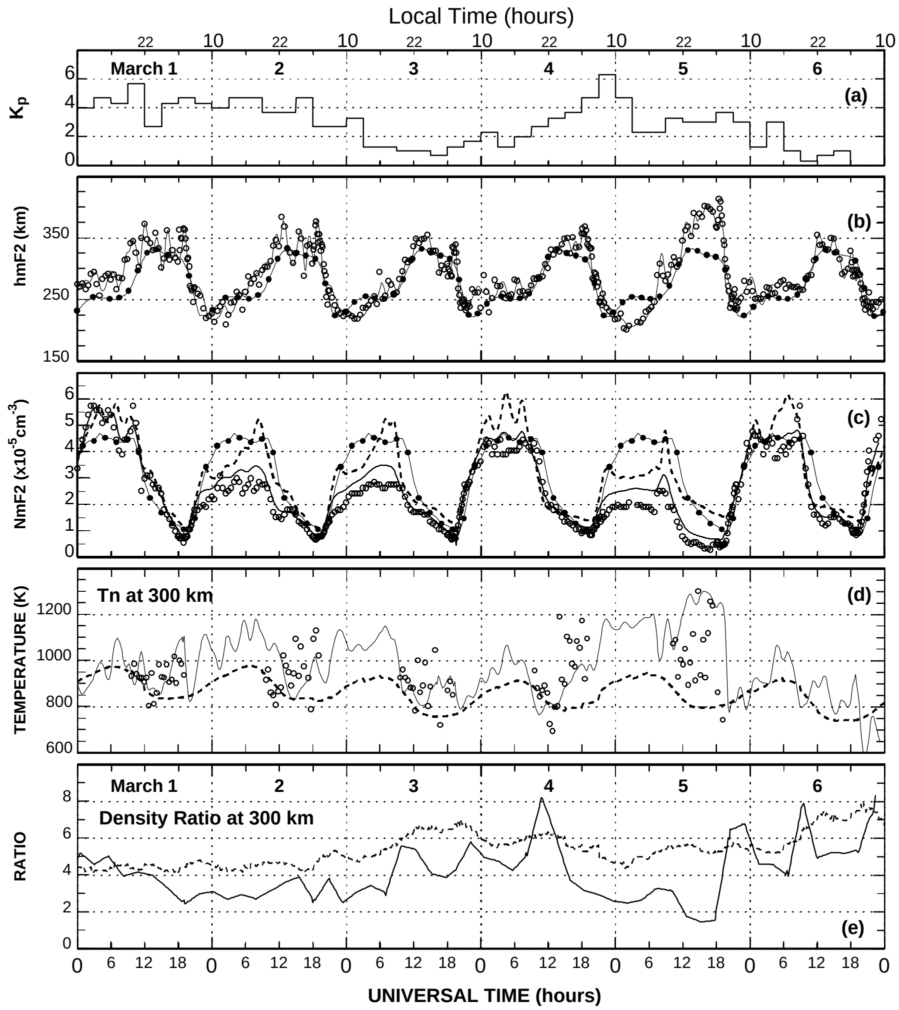


Figure 2. Calculated and observed parameters at Beveridge, Australia (38S, 147E) on March 1-6, 1995. Open circles -- measured values. Dashed lines -- standard MSIS. Solid lines -- modified MSIS. Lines/Dots -- Monthly Means.

Our March 1995 study described above and in more detail by *Richards et al*. [1998] illustrates the power of this neutral density modification algorithm to pinpoint discrepancies between the modeled and measured electron density that cannot be accounted for by nominal adjustments to the neutral atmosphere. In a separate study of the ionosphere over the Australian-Japanese sector during November 1993 [*Richards and Wilkinson*, 1998] we found very little modification of the MSIS model was needed most of the time to reproduce the measured electron densities.

In summary, the ability of the FLIP model to use key measurements as constraints makes it unique among time-dependent ionospheric physical models. Because the model uses data as constraints, and because the coupling to the plasmasphere and conjugate ionosphere eliminates the need for ad-hoc upper boundary particle and heat fluxes, there are few adjustable parameters. Thus, it is ideally suited to comparisons between model and data. Numerous previous studies indicate the EUVAC solar flux model and the MSIS neutral atmosphere model generally produce good agreement between modeled and measured ionospheric densities during magnetically quiet periods.

1.3 Proposed work

The proposed work is organized after the three sets of problems addressed above.

Task 1: Model CME parameters

We propose to use SOHO (LASCO/EIT), WIND field and plasma data as well as previous well-analyzed events and our streamer-flux-rope three-dimensional axisymmetric code to test and fine tune a CME geoeffective predictive code Specifically, for recently observed events, the EIT/LASCO observations of the evolution of loops and streamers, and velocity profiles will be used as the inputs to the model.. The events to be studied include the SHINE/GEM/CEDAR study events (January 6-7, 1997; April-May 1998; and the space weather week scheduled for September 1999). We will work closely with the SHINE/GEM/CEDAR community and will be aided by the fact that the PI and both CoIs are all active members of the community.

The WIND field and plasma information will be used to calculate solar wind input into the magnetosphere and the geoeffectiveness of the interplanetary input schemes (such as the Akasofu epsilon parameter, etc.). The upstream pre-event slow solar wind data will be incorporated into the model for each event. If the predictive code gives incorrect arrival times, the filament current profile will be adjusted accordingly. To model the magnetic properties of the underlying magnetic cloud, we will first use EIT observations to identify the size and configuration of the unstable streamer arcade. Next, we will use magnetograph high resolution photosphere magnetic field data (Big Bear, Kitt Peak or Stanford) to obtain the orientation and line of sight field strength of the arcade. In our model we will assume that the orientation of the magnetic cloud will be the same as for the arcade. We next will use the interplanetary measurements of the magnetic cloud by the WIND spacecraft at 1 AU to compare with model predictions. We realize that the magnetic field magnitude is only a line of sight component, and if the former is incorrect, this will be adjusted in the initial conditions for this case.

We will then go back and determine the pre-CME field configuration. We will set up accordingly the initial conditions for the simulation. We will also use the ISEE-3 interplanetary parameters upstream of the shock to use in the model as the slow solar wind that the shock/CME will be propagating into. We will next prescribe a perturbation on the basis of the increase of the transverse field which may, or may not, be recorded by Big Bear vector magnetograph. In case these measurements are not available, we could use an educated guess to determine the magnitude of the transverse field magnitude as we have done for our previous studies [*Wu et al.*, 1997a,b,c; 1999; *Wu and Guo*, 1997].

<u>Task 2: Correlate CME parameters with magnetic storms</u>

Another fundamental problem in forecasting magnetic storms is the large number of "false alarms", even if the CME hits the Earth's magnetosphere. The Gonzalez and Tsurutani (1987) criteria for a $D_{st} < -100$ nT magnetic storm is that the dawn-dusk interplanetary electric field is > 5 mV/M (this is almost equivalent to requiring the IMF B_S to be $\geq$10 nT) for T > 3 hrs. Such interplanetary regions can occur either in magnetic clouds or in the sheath plasma upstream of the ICME. This empirical criterion has been found to hold not only for solar maximum but also for solar minimum. Violations to this criterion have not been found to date.

As noted above, *Tsurutani et al*. [1988] found that 5 out of 6 CMEs during 1978-1979 did not have the nice B_S-B_N (or B_N-B_S) field rotation of a magnetic cloud. Out of the 46 high speed (led by shocks) CME events that did not cause a large magnetic storm, "eight had northward fields and the remainder had fields that were primarily in the ecliptic plane or had sufficiently out-of-ecliptic components but were highly fluctuating in time".

Although a great deal of effort (this proposal as well) has gone into trying to predict major magnetic storms, little effort has gone into understanding the false alarms. We will attempt to do this in this task.

We will use as a base these 46 events to determine if they were definitely not magnetic clouds and if so, what conditions were present at the source at the sun (it is possible that some of these events contained clouds oriented in the east-west direction). We will also include WIND non-cloud events as well in these analyses. The advantage of the latter is that not only do we have Big Bear, etc. ground observations, but the SOHO and Yohkoh observations as well. However unfortunately, there have been few non-cloud events to date.

Given the solar conditions for the non-cloud events, we will model their release, acceleration, and propagation to 1 AU similar to what was done in Task 1.

While it is known that CMEs cause magnetic storms, the coupling processes are poorly known at best. Therefore, an additional part of this task will be to explore the coupling mechanisms between the solar wind and the ionosphere. This will be done by investigating the correlation between CME physical parameters provided by our MHD code and geophysical indices, principally Kp and ap, required as inputs for the FLIP model. Precedence for such correlations exist [*Akasofu*, 1981, 1996; *Klimas et al.*, 1998, *Valdivia et al.*, 1996]. For example, both *Akasofu* [1981] and *Akasofu and Fry* [1986] determined empirical relations between AE and the epsilon energy parameter which is calculated by our MHD model. *Akasofu and Fry* [1986] extended these empirical relations to include both Kp and ap. More recently, Akasofu's group at Alaska has been trying to further unite the relationship between the solar wind and geophysical indices. As a final part of this proposed task, we plan to work in close contact with this group to extend these analyses in an effort to obtain accurate estimates of Kp and ap from solar wind parameters.

Task 3: Model Ionospheric Response

We will first test our ability to model the ionospheric response to previously analyzed CME events, using known values for the magnetic indices. We will attempt to model observed hmF2, NmF2, and temperature for each available event. The predicted response will then be compared with observations of total electron content from groundbased ionosondes and radars, and satellite measurements. The ionospheric investigation will include the magnitude of positive/negative storms, the links between storm phases and changes in composition, and the nature of these composition differences.

Negative storm phases are decreases in electron density with respect to quiet values while positive storm phases are increases in electron density with respect to quiet values. Good reviews of ionospheric storms have recently been given by *Rishbeth* [1991] and *Prölss* [1995]. The review by *Prölss* [1995] lists 15 possible causes of the positive phase and 16 possible causes of the negative phase. Proposed causes of positive storms include changes in neutral composition and horizontal transport, but the most likely cause is the uplifting of the *F*-layer by equatorward winds or electric fields in the early hours of a storm. Similarly, many mechanisms have been proposed for negative phases with changes in the atomic to molecular neutral density ratio being favored.

Next, we will repeat the investigation using indices empirically derived from our MHD calculations. The first set of investigations will provide basic information about the ionospheric response to CMEs. However, the studies using MHD-derived indices will a much better test of the potential predictive power of this analysis. In addition to verifying the validity of the coupling to the MHD code, this will also provide and excellent opportunity to model the ionospheric response to strong perturbations.

1.4 Personnel and management plan

The investigation will consist of the Principal Investigator (PI), Dr. S. T. Wu, two co-Investigators, Drs. P. G. Richards and G. A. Germany, a research associate, Dr. A. H. Wang, a post-doctoral student (half time) and one graduate student.

The PI will be solely responsible for the management and overall conduct of the research effort. He will also be responsible for running the solar-interplanetary dynamical analyses and, with the assistance of Dr. A. H. Wang, running the MHD numerical model and modifying it as necessary. The overall progress under Task 1 outlined above will be under her direction.

Dr. Germany will be responsible for running the FLIP model and, with Dr. Richards, interpreting the results. The overall progress under Task 3 outlined above will be under his direction. Dr. Richards will be responsible for maintaining the FLIP model and making any necessary modifications.

Drs. Wu and Germany will be jointly responsible for progress under Task 2.

Professor S. T. Wu is Distinguished Professor of the University of Alabama System and Director of the Center for Space Plasma and Aeronomic Research. He has established his expertise in the field of numerical magnetohydrodynamic (MHD) simulation and solar physics. He has been active and productive in solar physics research, with published contributions in *Solar Physics, Astrophysical Journal, Computational Physics, Computers and Fluids, Computer Methods in Applied Mechanics and Engineering, Journal of Geophysical Research, and Astrophysics and Space Science,* etc. Professor Wu is a key member of the authorship for a series of papers that describe the results of flare energy buildup and release due to shear motion, loop-like coronal transients, modeling of nonlinear force-free fields and non-ideal MHD descriptions of prominence formations. Professor Wu is an associate scientists for the NASA/ESA SOHO mission with the LASCO experiment. His responsibility for LASCO/SOHO is to develop and utilize available MHD models to interpret the observations and to offer explanations of the physical processes involved in the observed features. Professor Wu co-chair of the International Solar Cycle Study, 1998 - 2002 under the sponsorship of SCOSTEP/International Council of Scientific Unions.

1.5 Bibliography

Akasofu, S.-I., Prediction of development of geomagnetic storms using the solar wind-magnetosphere energy coupling function ε, *Planet. Space Sci.* 29, 1151-1158, 1981.

Akasofu, S.-I., and C. F. Fry, A first generation numerical geomagnetic storm prediction scheme, *Planet. Space Sci.*, 34, 77-92, 1986.

Akasofu, S.-I., New scheme provides a first step toward geomagnetic storm prediction, *EOS, Trans. AGU*, 77, No. 24, 225, 1996.

Gosling, J. T., McComas, D. J., Phillips, J. L., and Bame, S. J., *J. Geophys. Res.*, 96, 7831, 1991.

Guo, W. P. and S. T. Wu, A Magnetohydrodynamic Description of Coronal Helmet Streamers Containing a Cavity, *Astrophysical Journal*, 494, 419-429, 1998.

Harned, D., S., and W. Kerner, *J. Comp. Phys.*, 59, 108, 1985.

Harned, D. S. and D. D. Schnack, *J. Comp. Phys.*, 65, 57, 1986.

Hedin, A.E., MSIS-86 Thermospheric model, *J. Geophys. Res.*, *92* (A5), 4649-4662, 1987.

Hedin, A. E., Atomic oxygen modeling in the Upper Thermosphere, *Planet. Space Sci.*, *36*, 907, 1988.

Hu, Y. Q. and S. T. Wu, A Full-Implicit-Continuous-Eulerian (FICE) Scheme for Multidimensional Transient Magnetohydro-dynamic (MHD) Flows and Numerical Example, *J. of Comp. Phys*., 55(1), 33, 1984.

Jacobs, D. A. H., in Sparse Matrices and their Uses (ed. I. S. Duff), Academic Press, New York, 1981.

Klimas, A. J., et al., AL index prediction using data-derived nonlinear prediction filter, *Physics of Space Plasmas*, No. 15, 1998.

Mikic, Z., D. C. Barnes, and D. D. Schnack, *Astrophys. J*., 328, 830, 1988.

Mikiæ, Z. and J. A. Linker, 1994, *Astrophys. J.*, 430, 898.

Nagy, A.F., and P.M. Banks, Photoelectron fluxes in the ionosphere, *J. Geophys. Res.*, *75* (6260), 1970.

Prolss, G.W., Ionospheric F-Region Storms, in *Handbook of Atmospheric Electrodynamics*, edited by Volland, pp. 195-248, CRC Press, Boca Raton, 1995.

Richards, P. G., and K. D. Cole, Numerical simulation of the time-dependent heat energy equations for the magnetosphere, *Planet. Space Sci.*, *27*, 1343, 1979.

Richards, P. G., Thermal electron quenching of N(^2D): consequences for the ionospheric photoelectron flux and the thermal electron temperature, *Planet. Space Sci.*, *34*, 689, 1986.

Richards, P. G., An improved algorithm for determining neutral winds from the height of the F_2 peak electron density, *J. Geophys. Res.*, *96*, 17,839, 1991.

Richards, P. G., D. G. Torr, M. E. Hagan, and M. J. Buonsanto, A new algorithm for improved ionospheric electron density modeling, *Geophys. Res. Lett.*, *22*, 1385, 1995.

Richards, P. G., P. L. Dyson, T. P. Davies, M. L. Parkinson, and A. J. Reeves, The behavior of the ionosphere and thermosphere at a southern mid-latitude station during magnetic storms in early March 1995, *J. Geophys. Res.*, *103*, 26241, 1998.

Richards, P. G., and P. J. Wilkinson, The ionosphere and thermosphere at southern mid-latitudes during the November 1993 ionospheric storm: A comparison of measurement and modeling, *J. Geophys. Res.*, *103*, 9373, 1998.

Richards, P. G., J. A. Fennelly, and D. G. Torr, EUVAC: A solar EUV flux model for aeronomic calculations, *J. Geophys. Res*, *99* (A5), 8981-8992, 1994.

Rishbeth, H., F-Region storms and thermospheric dynamics, *J. Geomag. Geoelectr.*, *43* (Suppl.), 513-524, 1991.

Schunk, R.W., and A. F. Nagy, Electron temperatures in the F region of the ionosphere: Theory and observations, *Rev. Geophys. Space Phys.*, *16*, 355, 1978.

St-Maurice, J.P., and R.W. Schunk, Diffusion and heat flow equations for the mid_latitude topside ionosphere, *Planet. Space Sci.*, *25*, 907, 1977.

Steinolfson, R., S. T. Suess and S. T. Wu, *Astrophys. J*., 255, 730, 1982.

Sun, M. T., S. T. Wu, and M. Dryer, *J. Comp. Phys.*, 116, 330, 1995.

Torr, M. R., D. G. Torr, P. G. Richards, and S. P. Yung, Mid- and low-latitude model of thermospheric emissions, 1, $O^+(^2P)$ 7320 Å and N_2 (2P) 3371 Å , *J. Geophys. Res.*, *95*, 21,147, 1990.

Tsurutani, B. T., B. E. Goldstein, W. D. Gonzalez, and F. Tang, *Planet. Space Sci.*, 36, 205, 1988.

Valdivia, J. A., et al., Prediction of magnetic storm by nonlinear models, *Geophys. Res. Lett.*, 23, 2899, 1996.

Wang, A. H., S. T. Wu, S. T. Suess, and G. Poletto, *J. Geophys. Res*., 103, 1913, 1998.

Wu, S. T. and J. F. Wang, *Comp. Methods Applied Mech. Eng*. 64, 267, 1987.

Wu, S. T., and W. P. Guo, AGU Geophysical Monograph 99, Coronal Mass Ejections (N. Crooker, J. Joselyn, F. Feyman, eds.) AGU Press, Washington, DC 83, 1997.

Wu, S. T., W. P. Guo and J. F. Wang, Solar Phys., 157, 325, 1995.

Wu, S. T., A. H. Wang, and W. P. Guo, *Astrophys. and Space Science*, 243, 149, 1996.

Wu, S. T., W. P. Guo and M. Dryer, *Solar Phys*., 170, 265, 1997a.

Wu, S. T., W. P. Guo., M. D. Andrews, G. E. Brueckner, R. A. Howard, M. J. Koomen, C. M. Korendyke, D. J. Michels, J. D. Moses, D. G. Socker, K. P. Dere, P. L. Lamy, A. Llebaria, M. V. Bout, R. Schwenn, G. M. Simnett, D. K. Bedford, and C. J. Eyles, Solar Phys., 174, 719, 1997b.

Wu, S. T., W. P. Guo, D. J. Michels, M. D. Andrews, G. E. Brueckner, R. A. Howard, M. J. Koomen, C. M. Korendyke, J. D. Moses, D. G. Socker, K. P. Dere, J. L. Bougeret, P. L. Lamy, R. Schwenn, and G. M. Simnett, pp. 739-744, Proceedings of the Fifth SOHO Workshop, The Coronal and Solar Wind near Minimum Activity, Oslo, Norway, 17-20 June 1997, *ESA SP-404*, September 1997c.

Wu, S. T., W. P. Guo, D. J. Michels, and L. F. Burlaga, MHD description of the dynamical relationships between a flux rope, streamer, coronal mass ejection, and magnetic cloud: An analysis of the January 1997 Sun-Earth connection event, J. Geophys. Res. 104, 14,789, 1999.

1.6 Proposal-specific technical details

The DEPSCoR call for proposals specifically asked that the following points be addressed.

1.6.1 Plans for graduate students

The research team will include one full time graduate student and a post-doctoral researcher at 40% support. The students will have the opportunity to work with, interact with, and learn from the three principal researchers in the project.

1.6.2 Involvement with DoD and other centers

The investigators have a long history of collaboration with other centers (NASA MSFC, NOAA-SEC, NRL) and plan to continue that involvement in the work proposed here. Solar data will be obtained from SOHO/LASCO/EIT of which the PI is associate scientist. Over 50 years of ionosonde measurements are available from NGDC and will be used as part of the ionospheric modeling. The investigator team's work attests to their involvement with centers around the country as shown by the cited bibliography above. As a final test, we will work with the team at NOAA Space Environment Center/Air Force (Dr. E. Hildner and his colleagues) for real time testing of our final, combined prediction products.

1.6.3 Available facilities and proposed facilities/equipment

No support for facilities or equipment is requested as part of this proposal. The research will be conducted with the facilities of the UAH Center for Space Plasma and Aeronomic Research (CSPAR). CSPAR is a recognized center of excellence in space plasma, aeronomic, and astrophysical research. Established in 1986, it brings together faculty, research scientists, and students from the colleges of engineering and science at the University of Alabama in Huntsville. CSPAR's main computing platform is a cluster of DEC Alpha machines running OpenVMS. PC's running X-Server software provide a graphical interface to our Alpha systems as well as any other X-capable machines, they also provide their own processing power. The Alpha's and PC's replaced the combination of a DEC VAX cluster and graphics terminals which served the Center from 1987 through early 1994. The Alpha's provide a factor of 20 or more increase in processing speed, while the PC's add much greater flexibility to the user environment, and much easier and faster visualization of data and simulation results.

1.6.4 Rationale for requested equipment

N/A

1.6.5 Other parties who will receive or partial fund this proposal

This proposal is not being sent to any other agency. The University of Alabama in Huntsville will supply matching funds as outlined in the financial content at the end of this proposal.

2. Summary of evaluation points

For the convenience of the reviewer, this section is included to address the DEPSCoR-specific review criteria. Each of the six points below have been identified as evaluation points by which this proposal is to be judged.

2.1 Scientific and technical merits

The proposed work has high scientific merit in that it will lead to significant increases in our understanding of CMEs (initiation and propagation), their interaction with the Earth, and the ionospheric response to the solar events. The overall goal of the proposal is to investigate the feasibility of providing a self-consistent coupling between solar propagation models, which typically stop at 1 AU, and ionospheric models which assume an input function as a proxy to solar activity. Successful completion of this goal will mark the first time such a self-consistent coupling has been done.

The proposed work does not depend on the development of new tools or the use of inaccessible data sets. Much of the work will be done with previously analyzed events. In addition, the principal investigator is an associate scientist on the SOHO mission and has access to data from that, and related, space missions. For these reasons this proposal has high technical merit.

2.2 Potential contributions to defense missions

The AFOSR defense mission definition as defined in "RESEARCH INTERESTS OF THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH And BROAD AGENCY ANNOUNCEMENT 2000-1" (AFOSR 64-1) dated June 1999, states:

> "Our research interests include... coronal mass ejections (CMEs) and solar flares; the coupling between the solar wind, the magnetosphere, and the ionosphere; the origin and energization of magnetospheric plasma; and the triggering and temporal evolution of geomagnetic storms.
>
> "By specifying the flow of mass, momentum, and energy from the Sun to the Earth, and by forecasting the plasma phenomena that mediate the flow of energy through space, our goal is to develop a global, coupled solar-terrestrial model that connects solar activity with the deposition of energy in the Earth’s upper atmosphere."

The work proposed here directly addresses this mission by studying both solar and ionospheric events. It has a high potential of producing positive contributions due to the following factors.

1. The two principal models used in this work are mature products that have been highly development and tested. The modifications outlined to the MHD model are much smaller in scope in comparison to developing new numerical models.
2. This effort focuses on the sources (CME initiation and propagation) and ultimate effects (ionospheric responses) without attempting to address all the intervening details of magnetospheric energy storage and release. By parameterizing ionospheric responses in terms of CME physical parameters, the results of this work should be more amenable to existing space weather research efforts.
3. The analysis proposed here is a critical element in developing a predictive space weather capability. Successful completion of the tasks outlined above should provide direct contributions to space weather effort.

2.3 Broadened university base and education of scientists for DoD

The work proposed here has a high likelihood of enhancing existing research capabilities by coupling two models and research teams that traditionally have worked independently. This is a natural coupling in light of the problems investigated that encompass both solar and ionospheric topics. This work has high potential to contribute to the education of future scientists and engineers in disciplines critical to the DoD mission. The research team will include one full time graduate student and a post-doctoral researcher. The students will have the opportunity to work with, interact with, and learn from the three principal researchers in the project.

2.4 Qualifications of personnel

The three principal researchers together represent almost 60 years of scientific research experience. The PI has established his expertise in the field of numerical magnetohydrodynamic (MHD) simulation and solar physics. Dr. Wu is a key member of the authorship for a series of papers that describe CME initiation and propagation, flare energy buildup and release due to shear motion, modeling of nonlinear force-free fields and non-ideal MHD descriptions of prominence formations. Dr. Wu is an associate scientist for the NASA/ESA SOHO mission with the LASCO experiment. His responsibility for LASCO/SOHO is to develop and utilize available MHD models to interpret the observations and to offer explanations of the physical processes involved in the observed features.

Dr. Richards has likewise distinguished himself in the fields of ionospheric modeling and aeronomy. He has over 20 years research experience in space science with specialization in numerical techniques for the study of ionospheric transport phenomena, ionospheric chemistry, absorption of solar EUV and UV radiations, auroral electron precipitation, and ionospheric photoelectron theory. He is the principal author of the FLIP model and has overseen its development over its 20+ year history.

Dr. Germany has over 10 years experience in ionospheric/thermospheric modeling, specializing in the use of optical emissions as remote diagnostics of thermospheric composition and auroral processes. He is a member of the science team for the POLAR Ultraviolet Imager and has experience with both the FLIP and the UAH two-stream auroral deposition numerical models.

All three researchers have exemplary publication records and are highly qualified to conduct the proposed research.

2.5 Involvement with DoD and other centers

The investigators have a long history of collaboration with other centers (NASA MSFC, NOAA-SEC, NRL) and plan to continue that involvement in the work proposed here. Solar data will be obtained from SOHO/LASCO/EIT of which the PI is associate scientist. Over 50 years of ionosonde measurements are available from NGDC and will be used as part of the ionospheric modeling. The investigator team's work attests to their involvement with centers around the country as shown by the cited bibliography above. As a final test, we will work with the team at NOAA Space Environment Center/Air Force (Dr. E. Hildner and his colleagues) for real time testing of our final, combined prediction products.

2.6 Realism and reasonableness of financial content

Support is requested for salary, student support, and travel only. The amount of time requested for each researcher is a reasonable estimate of their participation in the project.